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Preliminary Investigation of a Novel Carbon Dioxide Laser for Applications in Dentistry

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Background and Objective: **A novel pulsed CO_2 laser was examined for its ability to ablate hard dental tissues.**
Study Design/Materials and Methods: **Lased human enamel surfaces were viewed using light and scanning electron microscopy for evidence of adverse structural changes. In vitro shear bond strength tests were conducted on composite resin bonded to lased enamel surfaces and compared with conventionally prepared specimens. A thermal camera was used to monitor temperature changes during cavity preparation in tooth slabs to assess likely changes to the dental pulp.**
Results: **No charring or surface cracks were observed on lased enamel surfaces using both microscopic techniques. Bonding of the lased enamel surfaces to composite resin was not significantly different from the acid-etched control group. For cavities with a remaining dentine thickness of less than 1 mm, the temperature rise was less than 6°C.**
Conclusion: **A novel pulsed CO_2 laser shows promise for cutting cavities in teeth. Lasers Surg. Med. 26:262–269, 2000**

Key words: **dental bonding; hard tissue ablation; pulp safety; pulp temperature; pulsed dental laser**

INTRODUCTION

From early on in their development, lasers have been investigated as a potential tool for ablating dental hard tissues with the aim of replacing the dental drill. Initial studies with the ruby laser [1–4] demonstrated that ablation of sound and carious dental hard tissues was possible, although very high irradiance levels were needed.

A main requirement for a dental laser to cause ablation is strong absorption by enamel and dentine. Carbon dioxide laser excitation wavelengths in the 9.3- to 10.6-μm range are well absorbed in these tissues, suggesting this laser would be suitable. The effects of the CO_2 laser on teeth have been examined. One of the early studies [5] that used a continuous beam CO_2 laser did not cause hard tissue removal but produced a large thermal loading within the tissue, which led to the formation of surface cracks and charring of dentine. Pulsed CO_2 lasers were then investigated for applications in dentistry, including inhibiting caries [6,7], etching [8], and desensitising dentine [8], although the search for an appropriate means of ablating dental tissues continued.

As laser technology has developed, pulsed CO_2 lasers of varying characteristics have been examined, with Brune [9] using pulses of over 1 ms at various energy densities to ablate enamel. Unfortunately, cracking around the cavity was noted, as was charring of the dentine where brown discolouration was noted. Using longer pulses [10] of 50-ms duration, hard tissue was also carbonised, and fissures along the crater walls and fused enamel bulging around the crater rim were reported. Unlike soft-tissue applications, for which charring may be sought so as to promote wound healing, thermally damaged dental hard tissue does not repair itself. This charring adversely affects the appearance of the tooth, perhaps even after restoration. In seeking a solution to this thermally induced tissue damage a range of other studies with short pulsed lasers

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have been performed. Using various pulse durations (0.1 to 130 μs), Ertl [11] reported that the CO_2 laser could cut enamel and dentine without any thermal damage only when using a water spray coincident with the laser beam, with the longer pulses proving the most effective cut. With a pulse duration of 1 μs and a low pulse repetition rate (0.1 Hz), Lukac [12] was able to cut enamel and dentine without thermal or structural damage. However, damage in dentine was noted when using 0.1-μs pulses. In addition, the CO_2 laser ablation was much slower than the 200-μs Er:YAG laser used for comparison in that study due to the plasma formed adjacent to the tissue surface acting as a shield for subsequent CO_2 laser pulses. Using 50-ns CO_2 laser pulses, without a coincident water spray, Meese [13] ablated carious dentine without carbonising the surrounding tissue by using low pulse repetition rates. However, sound dentine was removed much less effectively and no investigation of the effect on enamel was undertaken.

The different ablation rates and tissue responses observed for different CO_2 lasers reflects the dependence of the laser-tissue interaction on the duration, energy density, and repetition rate of the laser pulses, as well as the tissue spectral absorption. All these parameters influence the energy transfer process and, therefore, the type of interaction. Another influencing factor is the use of a coincident water spray, which is used with commercial Er:YAG dental lasers and affects the interaction process while cooling the surrounding tissue.

Because of considerable research efforts over the past 10 years or so, the pulsed Er:YAG laser has made a breakthrough as a clinically applicable laser drill [14] after experimental work demonstrated that the 250-μs laser pulses ablate enamel and dentine effectively [15] without causing peripheral damage [10]. Although slower at ablating hard tissue than a conventional dental handpiece, clinical reports of a reduction in pain experienced during cavity preparation with this laser suggests it may have a place in treating anxious or needle-phobic patients. The main drawback of the Er:YAG laser is its cost, which has restricted its use by dental practitioners. However, a less-expensive laser system could prove viable for cavity preparation procedures for these particular patient groups.

In this study, a prototype CO_2 laser with several novel features was investigated. In particular, this CO_2 laser delivers pulses in short bursts containing up to 10 pulses of around 100 to 700 μs duration with each pulse separated by around 250 μs. The laser beam is focussed to about 0.4-mm diameter and is automatically scanned around a 1 mm diameter to cause char-free ablation of dental hard tissues. In common with Er:YAG dental lasers, a water spray coinciding with the focal spot is delivered from the laser handpiece. As the laser output is generated using a conventional 20 W laser head, which may also be used to generate a continuous beam or long pulses (i.e., "superpulses"), this CO_2 laser is a potential multipurpose tool for use in medical and dental surgery. Also, because it is based on well-established laser technology, it is likely to be less expensive than present commercial Er:YAG dental lasers.

The aim of this preliminary study was to examine how well this new pulsed CO_2 laser meets the requirements for any cavity preparation system. In particular, assessments were made of the ability to cut the dental hard tissues without causing charring or cracking of the tooth surface using light and scanning electron microscopy. To determine whether the underlying surface was suitable for bonding to dental composites shear bond strength tests were performed. In addition, the thermal response during lasing was also monitored to determine whether heating of the remaining tissue would affect the pulp vitality.

MATERIALS AND METHODS

The prototype carbon dioxide laser (Oral Medic® 20/HT, Medical Laser Technologies, Inverkeithing, Scotland) used in this study produces groups of pulses each containing up to 10 individual pulses of around 100 to 700 μs duration, each separated by about 200 to 1,000 μs, with a peak energy around 10 to 50 mJ. An articulated arm delivers the laser beam to a handpiece where it is focussed to a 0.4-mm-diameter spot about 7 mm from the tip of the handpiece and automatically scanned in a circular manner around a 1-mm diameter. A water spray coincident with the focussed beam is delivered continuously by the handpiece. The laser incorporates a conventional 20 W laser tube, which is commonly used for many medical laser systems and is also able to generate a continuous beam or long pulses (i.e., "superpulses"), making it a suitable for use in medical and dental surgery.

Only three of the available laser settings were used: A1, A2, A4. The exact nature of the pulses at these settings was commercially sensi-

tive as a patent application was in progress (Patent No. PCT/GB/96/01002) but fell within the ranges outlined above, with the pulse energy increasing from A1 through to A4.

To check for the presence of charred hard dental tissue, cavities in extracted human teeth were created with the laser using A2 and A4 pulse settings and the surfaces of the cavities and the surrounding tissue were examined by using an optical microscope. Several magnifications were used.

A T300 scanning electron microscope (Jeol, Tokyo, Japan) was used to inspect the enamel surfaces of several lased teeth with cavities 1 to 2 mm in diameter. Before undertaking a scanning electron microscope (SEM) examination, samples must be gold coated, which means tooth specimens must undergo dehydration, which may inadvertently lead to surface cracking of the tooth. Instead, a low viscosity polyvinylsiloxane dental impression material (Extrude, Kerr Corporation, MN) was used to record the enamel surface details and an epoxy-resin replica made and then prepared for SEM examination. As the resin replica can be gold coated without prior dehydration, surface changes can be attributed solely to the laser energy interaction.

Slabs between 0.85- and 1.5-mm-thick were cut from extracted human teeth. Using either the A2 or A1 laser setting, the handpiece was held about 7 mm above the tooth surface and scanned across it by hand, to cut a cavity with an area of between 1 to 2 mm^2 at the surface and tapered slightly toward the cavity floor. The laser exposure time varied from 5 to 105 seconds, depending on the slab thickness and the diameter and depth of the cavity.

For all 11 tooth specimens, the rear surface temperature was monitored throughout the laser exposure by using a thermal camera positioned around 30 cm away. The maximal temperature rise was noted and the minimal thickness of the remaining tissue was measured by using a micrometer with a customised narrow bore.

The effectiveness of composite resin bonding to enamel irradiated with the CO_2 laser was compared with two groups of specimens exposed to a Twinlight Er:YAG laser (Fotona, Ljubljana, Slovenia). The Er:YAG laser has a 2.94-μm emission wavelength, produces 250-μs pulses and a focal spot of 0.5 mm diameter about 10 mm from the handpiece tip. This laser also directs the beam by means of an articulated arm to a handpiece and has a water spray coinciding with the focussed beam. A comparison was also made with a group prepared using the standard acid etching technique. Each group contained 15 specimens.

Group A specimens were acid etched in a conventional manner by applying 38% phosphoric acid gel (Etch-Rite, Pulpdent Corporation, MA) to enamel for 30 seconds, rinsed with water, and air-dried. One CO_2 laser condition was examined along with two Er:YAG exposure conditions: group B, A2 pulse setting, CO_2 laser; and for the Er:YAG laser; group C, 100 mJ/pulse at 5 Hz; and group D, 200 mJ/pulse at 5 Hz. For each of the lased groups, the enamel was irradiated for 60 seconds over a designated circular section (~19 mm^2) with the handpiece tip held above the surface to ensure the respective beam was focussed and moved by hand continuously over the target area, simulating a clinical laser etching technique. In addition, after lasing, all samples were acid etched as described above.

For each test group, Z-100 (shade A3.5) dental composite (3M Dental Products, St Paul, MN) was applied to the enamel surface, within an area enclosed by a stainless steel ring. Two 1-mm-thick increments were applied with each layer light cured for 1 minute (Aristolite, Litema GSD, Baden-Baden, Germany). Samples were then stored in water for 24 hours before compressive shear bond strength measurement using a NENE M3000 (Deltalab-NENE, Kettering, Northants, UK). The shearing arm, which gripped the steel ring enclosing the dental composite, had a cross-head speed of 1 mm/min.

RESULTS

A typical optical microscope view of an enamel surface lased using the A2 pulse setting is shown in Figure 1. There was no evidence of charring either on the walls of the cavity or around the periphery for any of the lased specimens.

The surface structure of cavities prepared by using A4, A2, and then A1 laser settings were examined under an SEM at various magnifications, as shown in Figure 2. In Figure 2A, a ring of unaltered enamel surrounds the upper section of a lased crater. A typical high magnification (×640) view of the cavity wall of a laser ablated tooth is shown in Figure 2B. For each cavity, the ablated surfaces were irregular, reflecting the small spot size of the laser and the manual manoeuvring of the laser handpiece across the dental hard tissues. Significantly, neither cracks nor carbonisa-

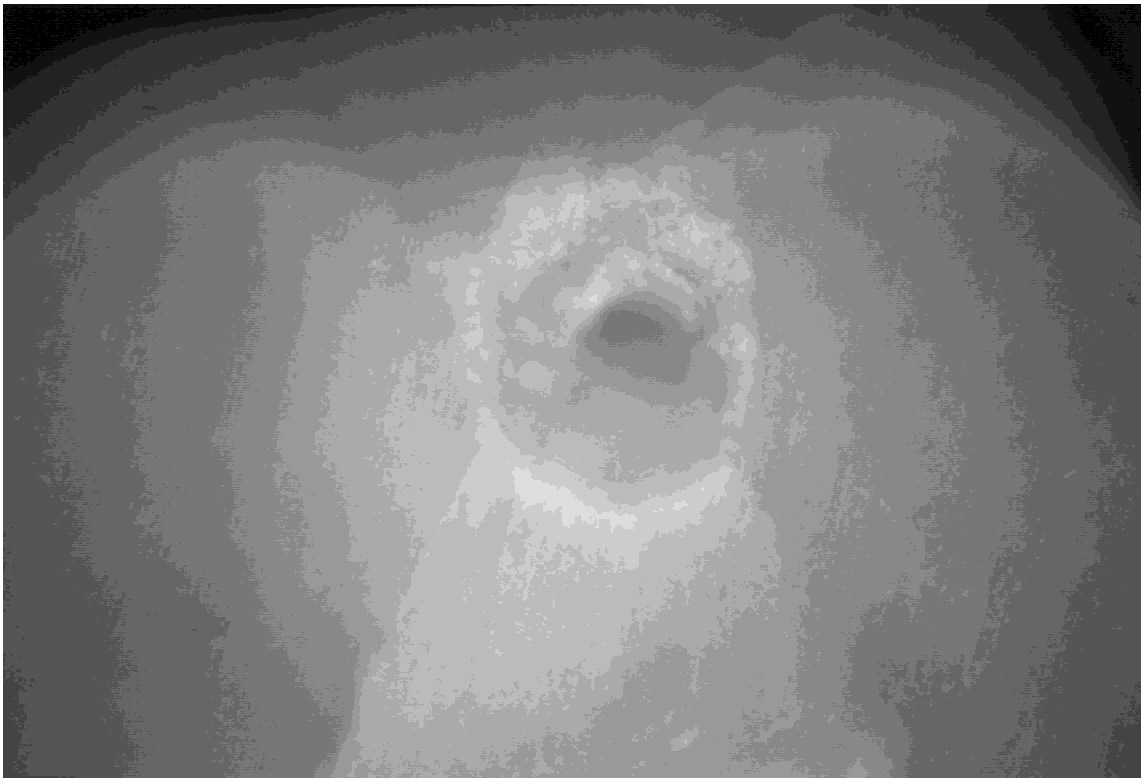

Fig. 1. Optical microscope view of a lased cavity of approximately 1-mm diameter, showing an absence of charred tissue.

tion were observed on the collateral tissue surfaces or the crater walls. There were signs of small amounts of tissue debris along the walls of a cavity, which were more than 2 mm deep (Fig. 2B).

The temperatures recorded during lasing are shown in Figure 3. There was no direct relationship between thermal loading of the cavity base and the remaining tissue thickness. Temperatures changes of more than 5°C were noted in two cases when using the higher pulse energy A2, where the remaining tissue thickness was 0.23 mm and 0.58 mm, respectively. Rises of less than 3°C were observed for tissue thicknesses of 0.3 mm and 0.81 mm. Using the lower energy A1 setting, even smaller temperature changes were noted.

The shear bond strengths measured are shown in Figure 4. Comparison using the one-way analysis of variance test showed that the acid-etched control, CO_2 laser, and 100 mJ Er:YAG laser groups (i.e., groups A, B, C, respectively) were not significantly different. The mean bond strength of the 200 mJ Er:YAG-lased group was significantly less ($P < 0.05$) than the acid-etched control group.

DISCUSSION

This study provide preliminary evidence by which to assess the potential of this novel pulsed CO_2 laser. There are numerous requirements for any tooth cutting instrument, several of which were assessed here. Although other criteria must be met, including for example an adequate ablation rate, any prospective dental laser must ablate hard dental tissues without causing thermal damage to these tissues or causing a thermal risk to the dental pulp, while providing a surface suited to bonding restorative materials.

The views of lased enamel obtained using the optical microscope provides evidence supporting the application of this laser to ablating dental tissue as no signs of charring were observed when the lower laser settings (i.e., A2, A1) were used. Although not shown here, the higher settings did cause slight charring of dentine. Previous CO_2 lasers have failed to cut tooth tissues without collateral damage, so blighting their application as a dental drill. Clearly, the combination of the specific pulse energies and pulse sequencing of the laser in this study with the use of a cooling water spray have overcome this problem. Also, there

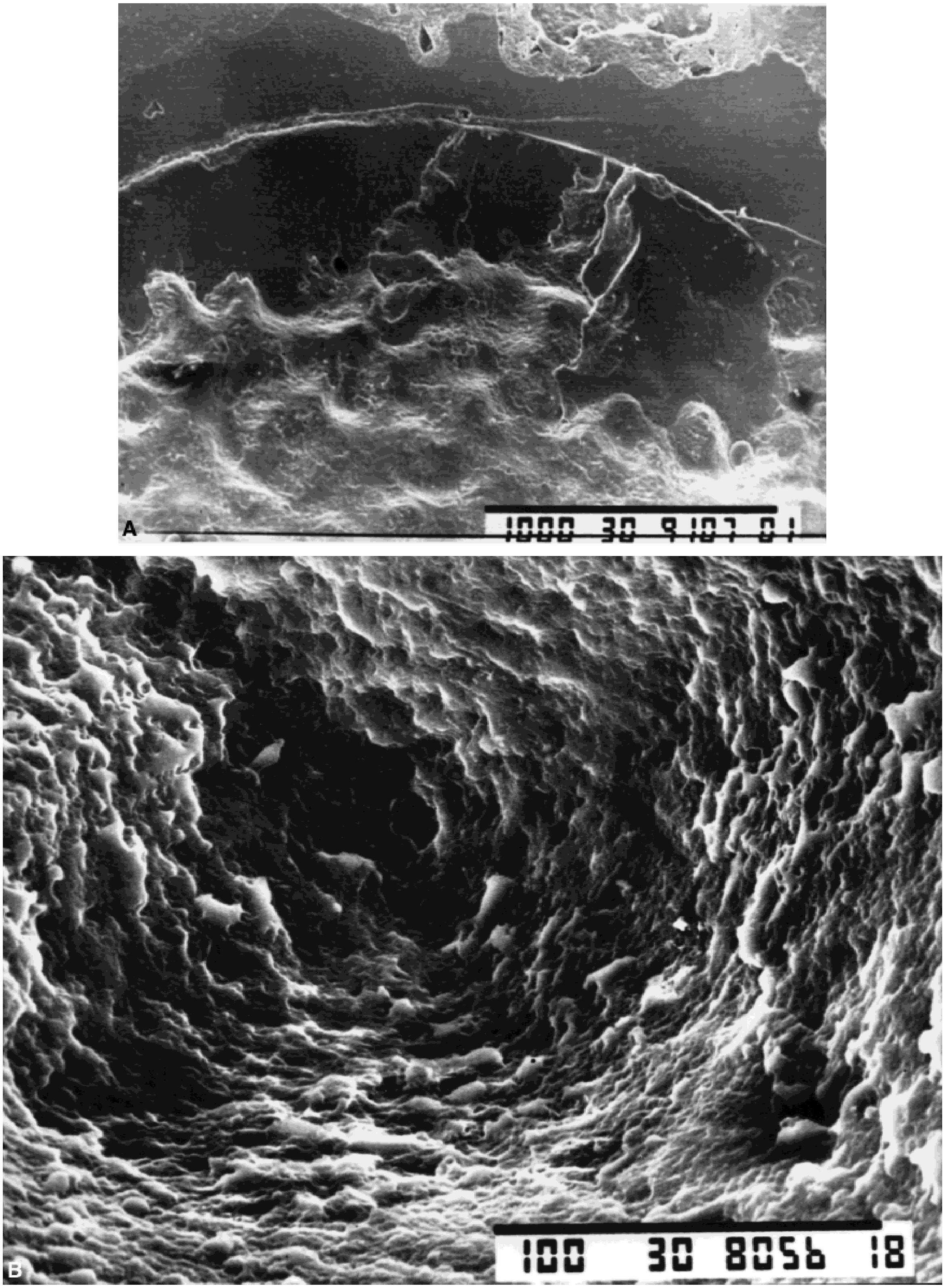

Fig. 2. Scanning electron microscope views of a CO_2-lased cavity using the A2 setting for ablating the bulk of the hard tissue, and then the A1 setting to finish at (**A**) × 64 magnification and (**B**) × 640 magnification. Note that in A there is a ring of unlased enamel around the cavity edge, and in B the cavity wall shown is about 1 mm or so below the sound enamel surface.

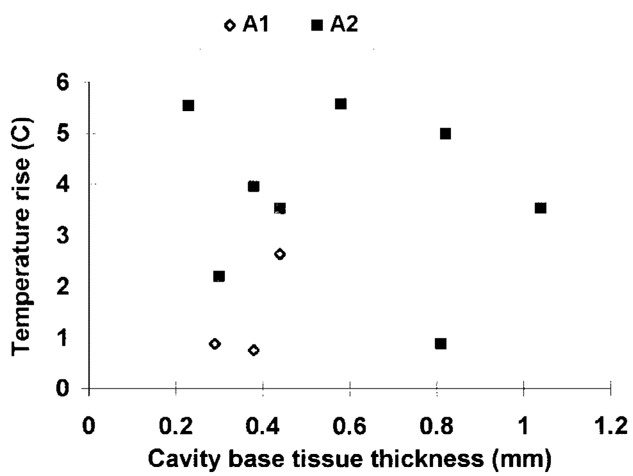

Fig. 3. The thermal response of the cavity floor rear surface during CO_2 laser tissue ablation of different tooth slabs using A1 (n = 3) and A2 (n = 8) pulse settings.

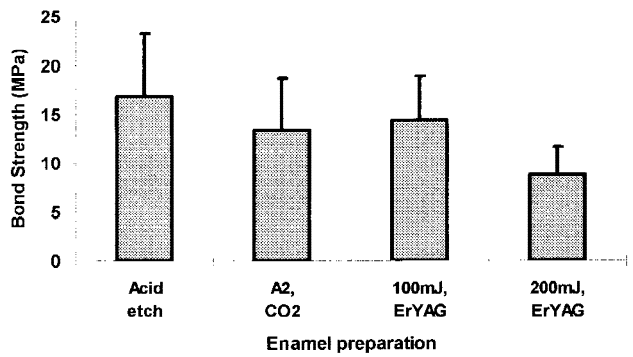

Fig. 4. Shear bond strength of composite resin to enamel (n = 15) prepared by using a conventional acid-etched technique (group A), the CO_2 laser (group B), and 100 mJ and 200 mJ Er:YAG laser pulse energies (groups C and D).

was no bulging around the cavity edge, which was reported for another pulsed CO_2 laser [10].

In some laser studies, cracks on tooth surfaces have been explained as being caused by artefacts of sample preparation, in particular the dehydration process before gold coating. However, this explanation has led to some doubts over the effect of lasers on hard-tissue surfaces and, therefore, laser usage itself. By preparing a resin replica of the lased surfaces for SEM investigation, this problem was avoided.

The CO_2 lased cavity surface is similar to the irregular form of the enamel and dentine surfaces after Er:YAG laser exposure [10] but with a less-pronounced flaky, scale-like appearance. There were no signs of melting, charring, or cracking of tissue, suggesting a thermomechanical tissue ablation mechanism for which vaporisation of surface water causes a microexplosion and the release of tissue fragments. The absence of surface cracks means the pressures created by subsurface water vaporisation were not catastrophic. This tissue response is markedly different from the molten surface and cracks noted in this previous study [10] when using a 50-ms CO_2 laser.

The in vitro temperature study was performed to simulate the laser-induced thermal loading of the dental pulp. By monitoring the rear surface of the cavity, the temperature experienced by the dental pulp tissue in contact with this dentine surface would be measured. It was assumed that the maximal temperature recorded would correspond to the point of minimal tissue thickness.

No clear relationship between peak temperature and minimal tissue thickness was observed (Fig. 3). Of course, the exact nature of the cavity, in particular thickness variations over its base, will affect heat transfer and, therefore, the temperature distribution around the cavity floor and the maximal temperature reached. The cavity bases created by manual manoeuvring of the laser handpiece were each of different shape, perhaps explaining the inconsistencies in the temperature-tissue thickness relationship. Another explanation may be the difficulty in delivering the water spray effectively to narrow cavities, especially when more than a few millimetres deep. Occasional fluctuations in the quality of the water spray supplied by using a hand-pressurised water reservoir system may also have influenced tissue cooling. These water spray fluctuations would not occur in permanently constructed laser systems.

In measuring only the minimal tissue thickness, a straightforward estimate of safe laser fluences could be made. Assessment of the safety of laser treatment is based on findings [16], which suggest that a rise of approximately 5.5°C causes no long-term harm to the dental pulp. Thus, for the A2 CO_2 laser setting, we estimate that the remaining dental hard tissue thickness should be around 1 mm to prevent thermal damage to the pulp. Clearly, using a lower laser fluence would generate less heat and, therefore, allow ablation of tissue layers closer to the dental pulp, albeit at a slower rate.

In addition to being able to cut through sound and carious hard dental tissues at a reasonable rate without cracking or charring of the surrounding tissue or significant thermal loading of the pulp, the CO_2 laser must produce a suitable enamel surface for restorative material (e.g., den-

tal composite) bonding. Some bonding studies to date have examined the CO_2 laser as an alternative to acid etching by using a range of exposure conditions — mostly with continuous or relatively long pulsed lasers [17–21]. Most CO_2 laser fluences have produced a markedly less-retentive surface than by acid etching, with only one laser exposure using 10-ms pulses [21] found to produce a better bond, while comparable bonding has been reported [17] after a 2-second exposure of a continuous beam laser. Notably, in the former report [21], bonding was markedly worse for the other test exposures, including one with a similar irradiance. As direct bonding of dental composites to CO_2-lased enamel have proven not to be consistent, and the specific purpose of this new dental laser is for ablating tissues and not for etching of enamel or dentine, an acid-etching stage was used after the laser cavity preparation in an attempt to ensure adequate bonding.

The bond strengths recorded here for the CO_2-lased/acid-etched specimens (group B) are comparable with the acid etch only samples (group A). It is likely that this bonding performance for group B is due to the acid-etched surface conditioning rather than the laser, because almost all other reports that used CO_2 laser conditioning alone have found low levels of composite resin retention. Nevertheless, enamel preparation using this pulsed CO_2 laser alone may provide adequate retention for restorative materials but this conclusion needs to be evaluated.

The low level CO_2 laser pulse energy used here (i.e., A2 setting) would probably be used for relatively slow tissue removal deep within a cavity, taking thermal loading of the nearby pulp into account, and so is a clinically relevant test condition. Although not investigated here, bonding to surfaces lased under other higher exposure conditions may also prove effective.

As the Er:YAG dental laser is now accepted for clinical use, it provides a benchmark for examining dental composite retention. The fact that composite-enamel retention using this new CO_2 laser compares favourably with acid and Er:YAG laser etching, suggests that, provided it ablates dental hard tissues effectively, this CO_2 laser may be an alternative dental tool.

Throughout these experiments, the laser handpiece was manually manoeuvred to simulate its clinical usage and ensure these findings should be similar to those experienced in clinical practice. Greater control over the handpiece manipulation may achieve more consistent results but may not provide as good a guide to the laser's clinical performance.

In conclusion, this dental laser prototype shows promise as an alternative to the conventional dental drill for preparing dental cavities. The lack of charring or surface cracking of the dental hard tissues, the fact that restorative materials can bond to lased enamel effectively, and that the thermal risk to the pulp can be effectively minimised through appropriate choice of laser setting and cavity depth supports this claim. An assessment of the ablation rate of enamel and dentine is needed to bolster these findings and allow a full performance comparison with other dental lasers. This CO_2 dental laser is also less expensive than the commercial Er:YAG dental laser systems and can be operated in other modes more suited to medical surgery applications, making it a multipurpose tool.

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